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Combustion Efficiency of Flares

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16. ABSTRACT The paper gives results of a study to provide data on industrial flare emissions. (Emissions of incompletely burned hydrocarbons from industrial flares may contribute to air pollution. Available data on flare emissions are sparse, and methods to sample operating flares are unavailable.) Tests were conducted on 3-, 6-, and 12-in. diameter flare heads. Propane was used as the flare fuel, diluted with nitrogen to control the heating value. The following results were obtained: (1) soot (from smoky flares) accounts for < 0.5% of the unburned hydrocarbon emissions; (2) the size of the flare head did not influence hydrocarbon combustion efficiency; and (3) the stability of the flare flame influenced combustion efficiency, with unstable flames tending to promote inefficient combustion. A relationship between gas heating value and exit velocity was developed to denote the region of flame instability.

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Abstract

Emissions of incompletely burned hydrocarbons from industrial flares may contribute to air pollution. Available data on flare emissions are sparse, and methods to sample operating flares are unavailable. The study reported herein was developed to provide additional data on flare emissions. A Flare Test Facility (FTF) was designed and constructed. Tests were conducted on 3-, 6-, and 12-in.* diameter flare heads. Propane was used as the flare fuel, diluted with nitrogen to control the heating value. The following results were obtained: 1) soot (from smoky flares) accounts for less than 0.5 percent of the unburned hydrocarbon emissions; 2) the size of the flare head did not influence hydrocarbon combustion efficiency; 3) the stability of the flare flame influenced combustion efficiency, with unstable flames tending to promote inefficient combustion. A relationship between gas heating value and exit velocity was developed to denote the region of flame instability.

(*)To convert to metric equivalent, please use the conversion factors listed at the end of this paper.

Flares

Flares are used to safely, efficiently, and economically destroy industrial gases from which the heating value cannot be economically recovered. The gases flared are typically the results of leaks, purges, and emergency releases. Table 1 indicates that over 16 million tons of such gases are flared in the United States from petroleum production, refineries, blast furnaces, coke ovens, and the chemical industry. The estimates are uncertain because the flow of gases to flares is usually uncontrolled and rarely measured.

The combustion efficiency of large commercial flare flames has not been measured. Such flames may be elevated 400 ft above the ground, burn gases on heads up to 12 ft in diameter, and produce flames over 400 ft long. Physically sampling such flames would be extremely difficult, and adequate optical (2) and remote sampling techniques have not been sufficiently developed.

In the absence of direct measurements of combustion efficiency of commercial flare flames, measurements of combustion efficiency have been made on laboratory and small pilot-scale flare flames. These data have been reviewed (3,4) and are presented in Table 2. The combustion efficiency of these small flames has been measured to approach 100 percent, but has also been measured to be as low as 55 percent.

The previous laboratory and pilot-scale studies left a number of unresolved questions concerning the efficiency of those flames:

- How does soot affect the measured combustion efficiency?
- Can overall flare combustion efficiency be estimated from measurements at a single position?
- How does the inability to close a mass balance influence the estimated combustion efficiencies?
- How can the results be extrapolated to large commercial flares?
- Which operating conditions of a flare result in low combustion efficiencies?

This study was designed to answer these questions.

Flare Test Facility

A large Flare Test Facility (FTF) was designed and built by Energy and Environmental Research (EER) Corporation in Irvine, California, under the sponsorship of the U.S. Environmental Protection Agency. The FTF is capable

TABLE 1. ESTIMATE OF THE AMOUNT OF GAS FLARED IN THE UNITED STATES IN 1980[1]

INDUSTRY	PRODUCTION 10^6 TONS/YR	PERCENT FLARED	AMOUNT FLARED 10^6 TONS/YR	10^6 MBTU/YR
Refineries	1048	0.2	2.1	103
Petroleum Production	584	0.5	2.9	116
Blast Furnaces[a]	146	6.6	9.6	69
Coke Ovens[a]	55	0.4	0.2	11
Chemical Industry[a]	60	2.0	1.2	59
		TOTAL	16.0	358

[a]Combustible gases only

TABLE 2. COMBUSTION EFFICIENCY OF FLARE FLAMES MEASURED IN PREVIOUS STUDIES

STUDY	DATE	FLARE SIZE IN.	DESIGN	VELOCITY FT/SEC	GAS FLARED	MEASURED EFFICIENCY %
Palmer (5)	1972	0.5	Exp. Nozzle	50 - 250	Ethylene	> 97.8
Lee & Whipple (6)	1981	2.0	Holes in 2" Cap	1.8	Propane	96 - 100
Siegel (7)	1980	27.	Comm Flaregas Coanda FS-6	0.7 - 16	Refinery Gas[a]	97 - > 99
Howes, et al. (2)	1981	6.	Comm. Air Assist Zink LH	40 - 60	Propane	92 - 100
Howes, et al. (2)	1981	3 at 4[b]	Comm H.P. Zink LRGO	80	Natural Gas	> 99
McDaniel (8)	1983	8	Comm Zink STF-S-8	0.03 - 62	Propylene/Nitrogen[d]	67 - 100
McDaniel (8)	1983	c	Comm Air Assist Zink STF-LH-457-5	1.4 - 218	Propylene/Nitrogen[e]	55 - 100

[a]50% hydrogen plus light hydrocarbons

[b]Three nozzles of 4 in. each

[c]Supplied through spiders; high Btu gas through area of 5.30 $in.^2$ and low Btu gas through 11.24 $in.^2$

[d]Heating value was varied from 209 to 2183 Btu/scf

[e]Heating value was varied from 83 to 2183 Btu/scf

of testing large pilot-scale and small commercial flare tips and has been thoroughly described elsewhere (4,9). The FTF was built in a box canyon at EER's El Toro test site to help protect the flame from the influence of wind. Most of the flames reported here burned mixtures of commercial propane and nitrogen. The mixed fuel can be delivered at rates up to 28,000 ft^3/hr. Propane and nitrogen are stored as liquids and vaporized for delivery to the flare system. Commercial natural gas is also available on site, and other gases could easily be delivered to the flare. The wide range of flow rates are accurately monitored using parallel calibrated flow orifices. Small amounts of SO_2 are vaporized from a liquid tank and delivered to the flare as a tracer to confirm material balances. Steam can be supplied at 1400 lb per hour by a 15 HP boiler for tests of the influence of steam injection on flare flame performance.

The flare head is enclosed in a 20 ft by 30 ft scaffolding 60 ft high. The scaffolding supports screens with 22.7 percent open area to further protect the flame from the wind, a 13 ft 8 in. square hood, and a five-position rake probe. The hood is used to capture, mix, and sample the complete effluent from small flames to confirm material balances, and the movable rake probe is used to measure detailed concentration profiles above the flames. Concentrations of O_2, CO_2, CO, HC, SO_2, and soot are measured. Soot is captured on a filter at the end of the probe, and its concentration is determined by burning it from the filter. Gases are maintained in heated lines to avoid condensation until water is removed by Permapur® driers. Samples are simultaneously drawn from different positions into Tedlar® bags for 20 minutes to average flame fluctuations. The gases are analyzed using continuous monitors and corrected for the composition of the background gases and dilution through material balances. For instance, the dilution factors are calculated from:

$$DF = \frac{[\,]_{measured} - [\,]_{SR=1,\ theoretical}}{[\,]_{background} - [\,]_{measured}} \qquad (1)$$

The concentration of stoichiometric combustion products is calculated from:

$$[\,]_{SR=1} = [\,]_{measured} + DF\left([\,]_{measured} - [\,]_{background}\right) \qquad (2)$$

The local combustion efficiencies are calculated from:

$$\eta = 1 - \frac{[CO]_{SF=1} + [HC]_{SR=1} + [soot]_{SR=1}}{[CO2]_{SR=1} + [CO]_{SR=1} + [HC]_{SR=1} + [soot]_{SR=1}} \qquad (3)$$

where DF, the dilution factor, is equal to the volume of air divided by the volume of combustion products; [ ] is the concentration of O_2, CO_2, or SO_2, measured in the plume; background is the concentration in the atmosphere; and SR = 1 is a theoretical concentration of combustion products calculated for stoichiometric combustion with pure air.

The local combustion efficiency (i.e., combustion efficiency at the sample location) is η. The local combustion efficiencies for samples taken with the hood are also overall combustion efficiencies (i.e., the overall combustion efficiency of the flame). The maximum error in local combustion efficiency is calculated at each location.

The overall combustion efficiencies are obtained by properly weighing the sample by probe area and estimated velocities and summing these values across the flame plume. The overall combustion efficiency is:

$$E = 1 - \frac{\Sigma_i \Sigma_r C_{i,r} V_r A_r}{\Sigma_j \Sigma_r C_{j,r} V_r A_r} \qquad (4)$$

where E is the overall combustion efficiency, C_i's are unburnt hydrocarbons (i.e., CO, HC, and soot), C_j's are all hydrocarbons, V_r is the average velocity through the area from which the probe sampled, and A_r is the area. The axis of symmetry is located from the experimentally determined dilution factors (see Figure 1). The velocities are estimated using jet theory from:

$$V_m = V_o \left[0.16 \frac{x}{d} - 1.5\right] \qquad (5)$$

and

$$V_{r,x} = V_m \exp\left[-90 \left(\frac{r}{x}\right)^2\right] \qquad (6)$$

where V_m is the centerline velocity, V_o is the velocity at the flare head, x is the axial distance above the flare head, d is the diameter of the flare head, $V_{r,x}$ is the local gas velocity at radial distance r and axial distance x. The velocities are known to be approximate (4,9), but the global combustion efficiencies are weighted toward the axis of the flame and some cancellation of the errors in the velocities results from the nature of Equation 4.

The structure of the flames was also investigated. A platform at the same height as the flare head and a background grid were used for visual observations, photography, and cinematography of the flare flames. The

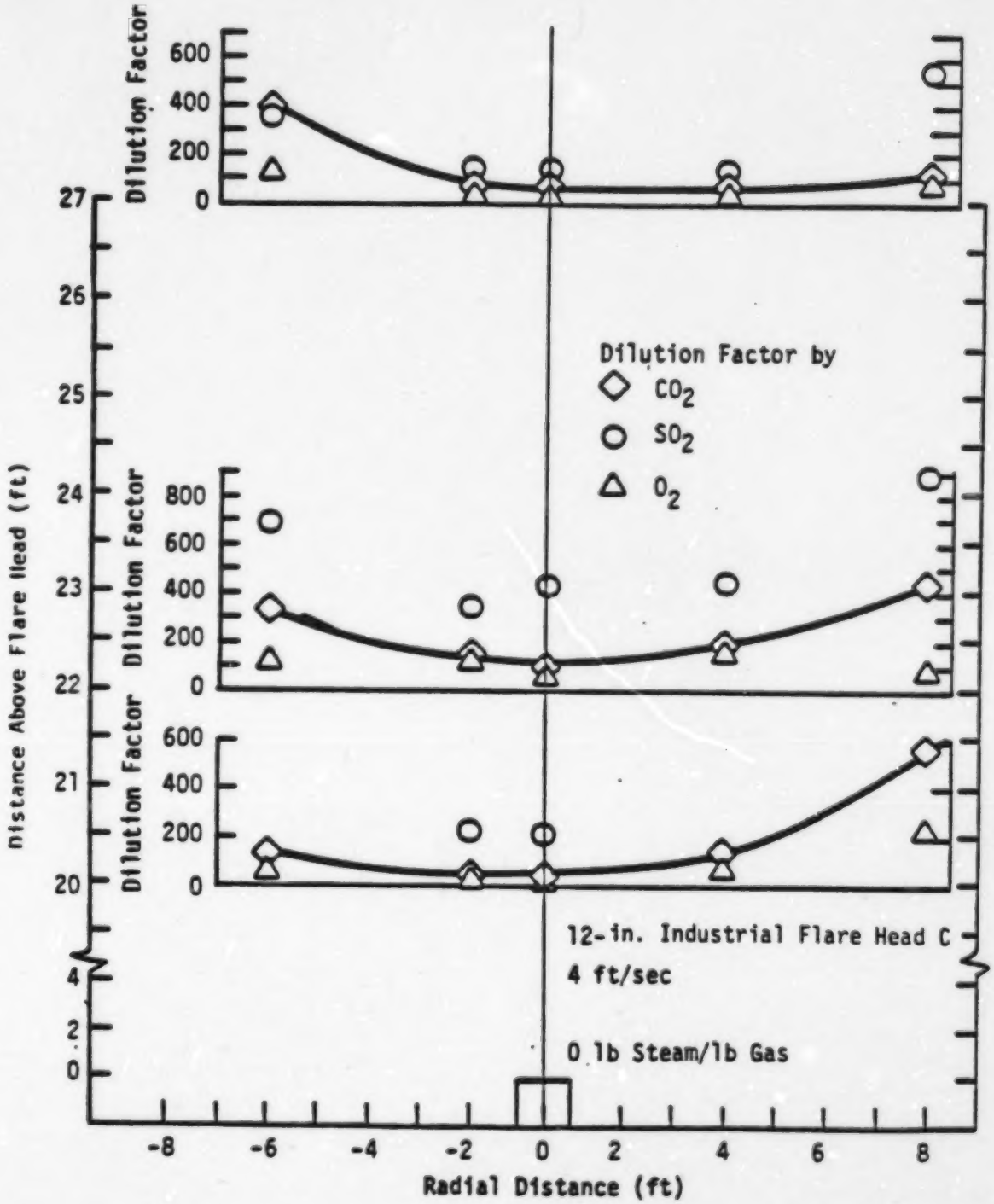


Figure 1. Dilution factor of the 12-in. industrial flare head C burning 56 percent propane in nitrogen at 4.0 ft/sec with 0.0 lb steam per lb of fuel.

buoyant flames investigated here do not have well defined flame lengths because of the intermittent formation and combustion of large pockets of gas. Values of the flame shape are average values of visible flames taken from visual observations, photographs with 1 and 20 m sec exposures, and motion pictures taken at 200 - 400 frames per second. The physical structure of the flames, flame length, entrainment rate, liftoff, and stability will be reported (9). The photographs and motion pictures were also analyzed for frequency, size, and behavior of luminous eddy structures which will be reported separately.

Results

This paper answers several unresolved questions about flare flames: 1) soot usually has a minor influence on measured combustion efficiency, 2) measurements of combustion efficiency at a single point can indicate the overall combustion efficiency of flares but may be in error, 3) strict closure of a mass balance is unncessary to measure the combustion efficiency of flares, and 4) the head size did not influence the combustion efficiency on heads of 3-, 6-, and 12-in. in diameter. The study concluded that operation of a flame near the limit of flame stability may result in poor combustion efficiency.

Soot concentration has a minor influence on the combustion efficiency of flares. Soot was measured for all points and conditions in these tests and was found to account for less than 0.5 percent of the combustion inefficiencies for most of the conditions tested (see Figure 2). This level of soot, however, will make the flames appear sooty and luminous.

The level of soot, luminosity, or sooty appearance was found to poorly correlate with combustion efficiencies of the flames. This results from the difference in time and conditions required to burn or quench heterogeneous material (soot) compared to homogeneous material (gaseous hydrocarbons). For instance, incompletely burned hydrocarbons have large oxidation rate constants and can burn completely in or near the flame, while soot has a lower oxidation rate constant and oxidation may be quenched before completion.

Steam is injected into commercial flare flames to suppress luminosity (i.e., soot). Results of this program showed: 1) less than 0.5 percent soot is usually present in sooty flames, 2) 0.5 lb of steam per pound of fuel completely suppresses this soot, and 3) soot remains suppressed at steam injections of more than 0.5 lb of steam per pound of fuel, but combustion of the hydrocarbons is quenched and the combustion efficiency of the flare is reduced.

Combustion efficiency measured at a single point results in over-estimating overall combustion efficiency. Ignoring the influence of velocity profiles in Equations 5 and 6, overall combustion efficiency can be written as:

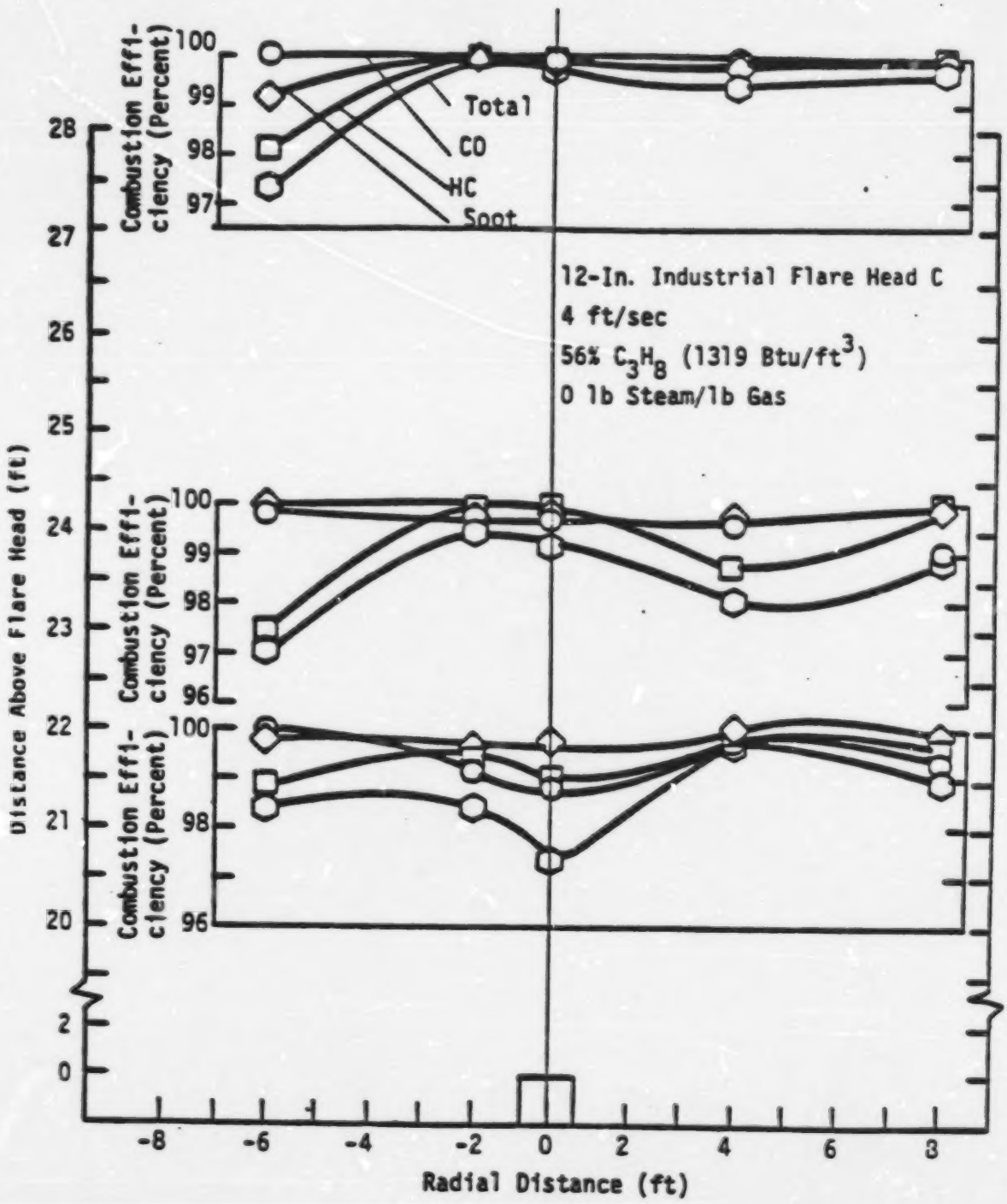


Figure 2. Local combustion efficiencies of the 12-in. industrial flare head C burning 56 percent propane in nitrogen at 4.0 ft/sec with 0.0 lb steam per lb of fuel.

$$E = 1 - \Sigma_r \frac{\Sigma_i C_{i,r} \Omega_r}{\Sigma_j C_{j,r}} \qquad (7)$$

where Ω_r is intermittency (i.e., the fraction of the time the flame is present at position r). A single measurement of local combustion efficiency will be the same as the overall combustion efficiency when either C_i and C_j or the intermittency factor Ω_r do not vary. Figure 2 shows that local combustion efficiencies vary with radial distance and are lowest at the edge of the flames. In addition, the intermittency factor is known to vary between 0 and 1 (10). The consequence is that the local combustion efficiency measured on the axis of the flare head overestimates the overall combustion efficiency of the flame. In practice, the error is slight, usually less than 50 percent of the combustion inefficiency measured; i.e., 50% of 1% = $\pm$ 0.5%.

Closure of a mass balance was found to be unnecessary to accurately determine overal combustion efficiencies. Mass balances were closed within 20 percent by two techniques in this study. First, the entire plume was captured in the hood. Second, SO_2 was used as a tracer to determine the mass flow of the plume and, hence, carbon flux. Both techniques proved that the combustion efficiency measured by probing techniques accurately determined the combustion efficiency of the flame. This could result from nearly complete determination of all carbon species or by the combustion efficiency of the gases determined by the probe being the same as the gas not sampled. In either case, mass balances have demonstrated the accuracy of the probing techniques used in this study.

The size of the flare head did not influence the combustion efficiency for the flare heads of this study. In general, this would imply that the combustion efficiencies measured on large pilot-scale flare heads are directly applicable to commercial flare heads. Figure 3 compares the range of conditions of this study with those of commercial flare heads. The conditions of this study approximate those of commercial flare heads with minor differences. The commercial flare heads are typically larger, 24 - 48 in., than those of this study. However, commercial flare heads range in size from 1.5 in. to 140 in., and three 12 in. commercial flare heads supplied by different vendors were tested in this program. The Richardson numbers of this study vary from 10^{-5} to 10^{3}, while the Richardson numbers of commercial flare heads vary from 15 to 10^{4}. However, this study included the influence of large Richardson numbers since all conditions with Richardson numbers greater than 1 will be largely influenced by buoyancy forces.

The combustion efficiency of flares operating near the stability limit may be low. The flame stability limit is simply the conditions at which the flame is maintained; flame instability occurs when the jet velocity exceeds the flame velocity and the flame goes out. Figure 4 shows the gas heating value versus the gas exit velocity at the point of instability (i.e., at the point where the flame starts to go out). This point is determined by establishing a propane/nitrogen flame at a given velocity and then

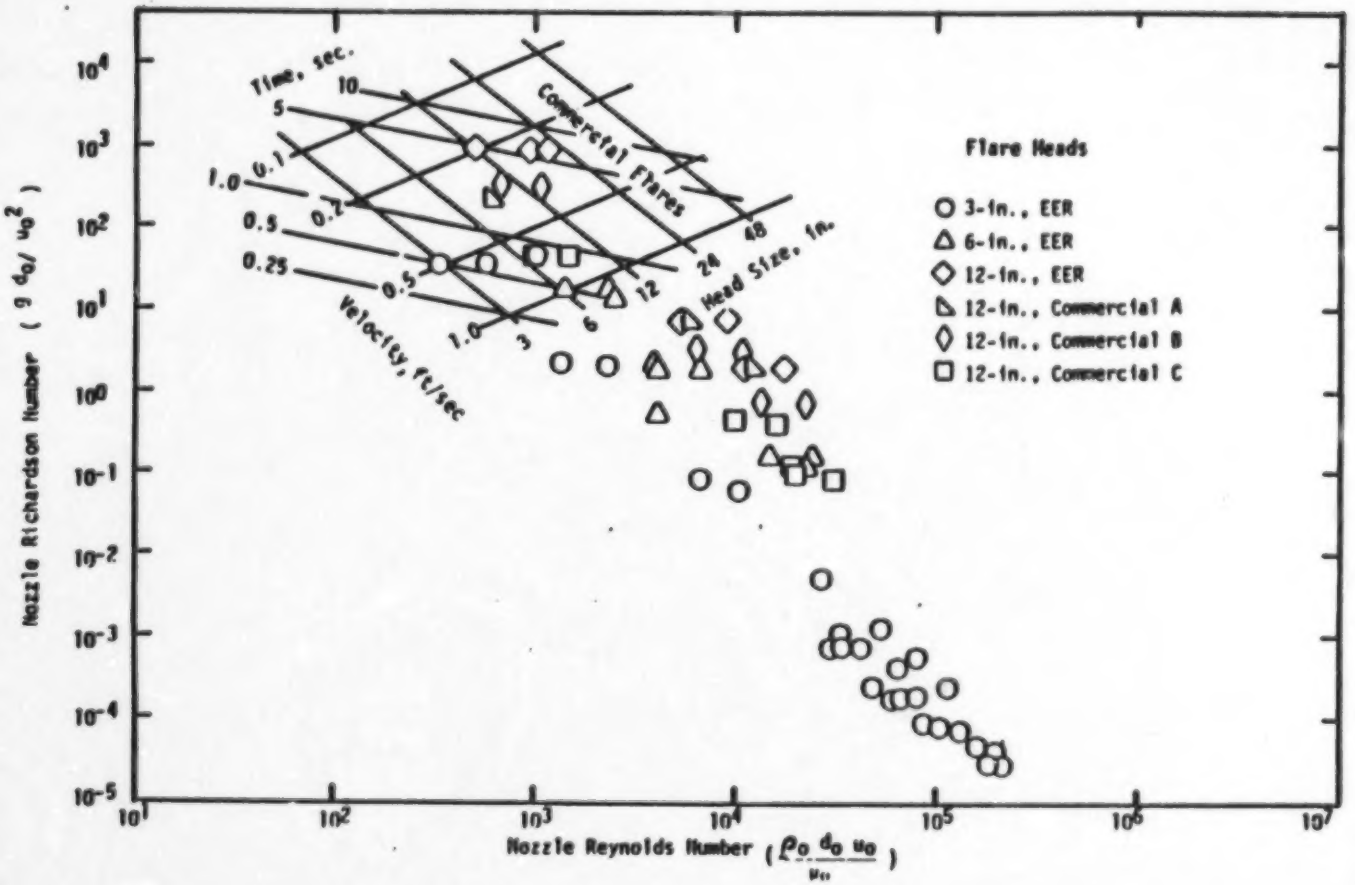


Figure 3. Comparison of the range of conditions tested in this study and those of commercial flare flames.

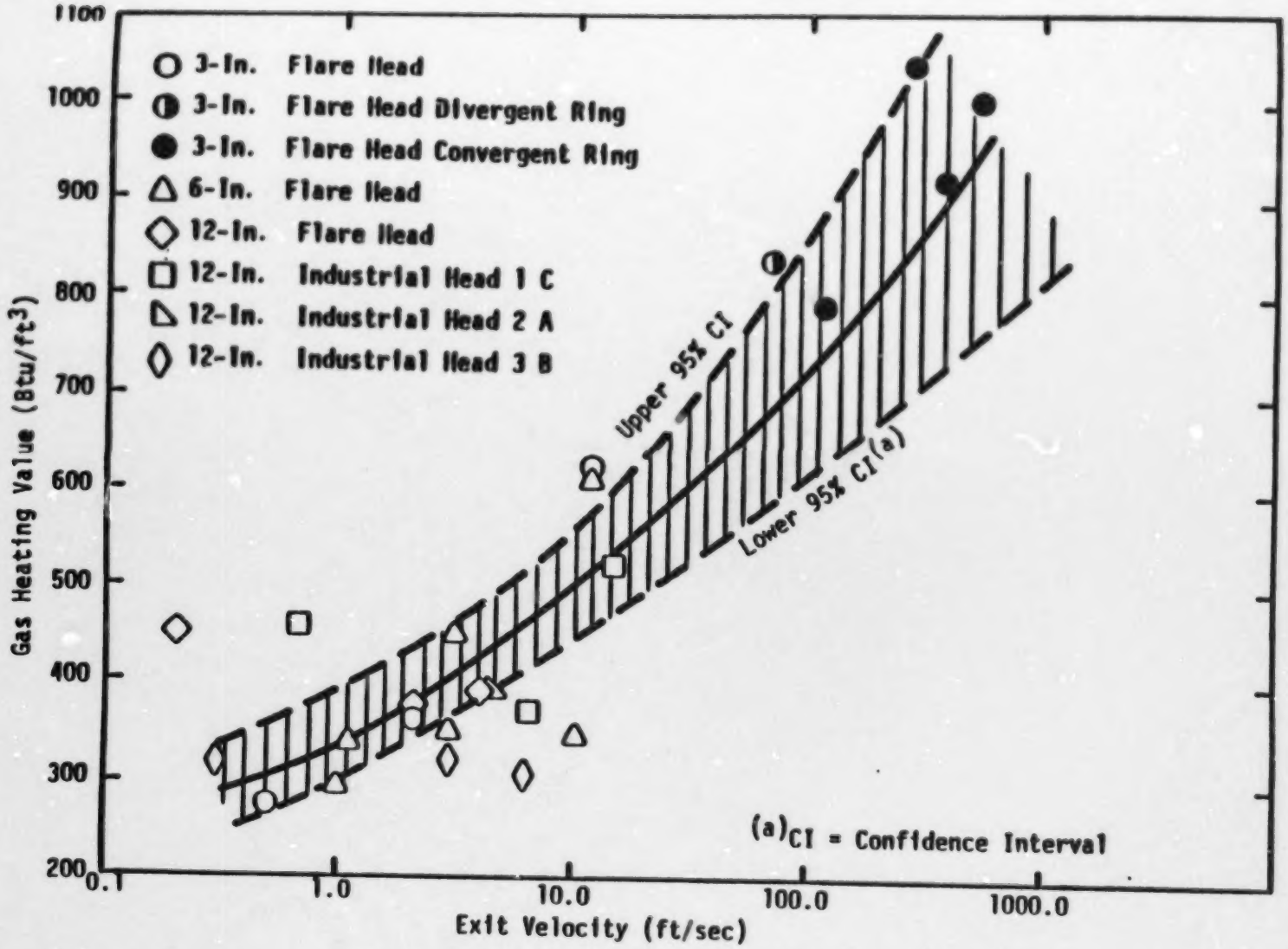


Figure 4. Region of flame instability.

decreasing the flow of propane until the flame goes out. The combustion efficiency is then measured at the conditions just prior to extinguishing the flame. Flare flames operating well above the limit of stability have combustion efficiencies greater than 98 percent.

The stability of a flame results from a balance of an imposed velocity and a flame speed (i.e., the combustible mixture is consumed at the same rate as fed to the flame). The flame speed is a result of mass transport to the flame zone and rapid combustion within this zone. The flame speed depends on the temperature of the flame, the nature of the material in the flame zone, and transport of the material to the flame zone. As a result, a relationship, shown in Figure 4, is expected between velocity and heating value for a fixed combustible. In this case, the combustible is propane.

The relationship between heating value and velocity for propane/nitrogen mixtures is generally good. However, some scatter is evident. The shaded area represents 95 percent confidence intervals for the mean of the relation. A large portion of the scatter is thought to be the result of operating a large exposed flame near the point of stability where slight perturbations will result in large variations in the flame stability. To a lesser extent, some of the scatter may be attributed to difference in design of commercial flare heads. However, judging from the scatter of individual flare head designs, the influence of design on stability is thought to be small.

Typically, commercial flames are supported with pilot lights. None of the flames of this study were supported with pilot lights because, under the conditions of low flow, the premixed efficient pilot light obscures the combustion efficiency of the flare. The influence of pilot flames on flare flame stability will be evaluated in future studies.

Stability limits of propane/nitrogen mixtures without pilot flames correlate with an Arrhenius plot using a pseudo-adiabatic flame temperature. This is reasonable, since the flame velocity is related to the kinetic consumption of the fuel. Such a correlation is shown in Figure 5, where C_p is the heat capacity of air, X is the mole fraction of propane in the flared gas, Q is the heat of combustion of pure propane, and 26 is a factor to account for the change in the number of moles on combustion of propane. This relationship has not yet been demonstrated for other gases, although the flame speeds of many gases have been shown to correlate with similar relations (4).

Combustion efficiencies of flares may be low only for conditions near the stability limit of the flames. Figure 6 shows the combustion efficiency of a number of propane/nitrogen flames. The line is the least-squares fit from Figure 4. Except for one point, all conditions which yield combustion efficiencies less than 98 percent are at or below the limit of flame stability. Some flames operating near the limit of flame stability had high combustion efficiencies. However, the potential to produce a flame with low combustion efficiencies always exists near the stability limit, and any small perturbation could result in a flame with poor combustion efficiency.

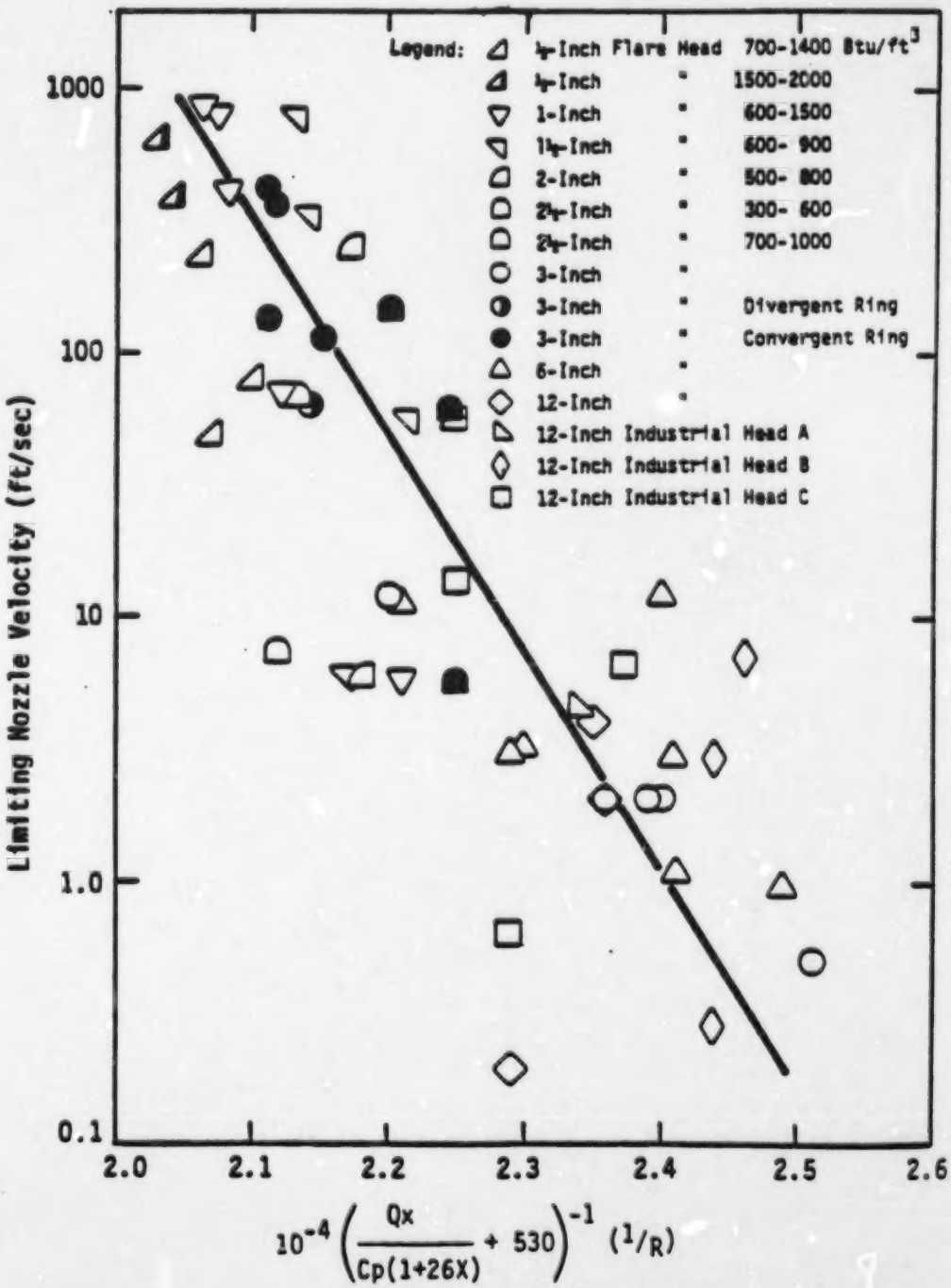
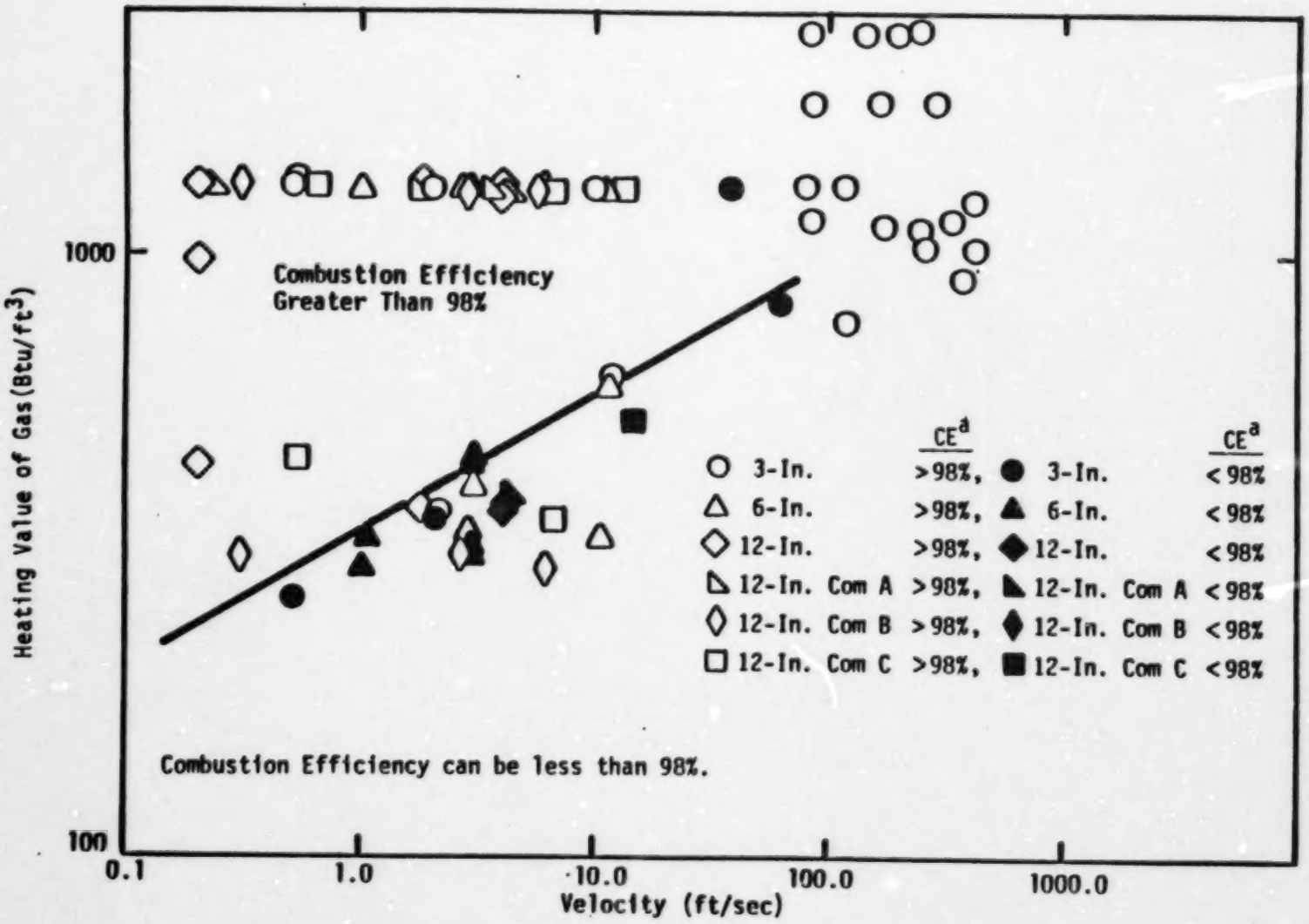


Figure 5. Limits of flame stability as a function of estimated temperature.



[a]CE = Combustion Efficiency

Figure 6. Conditions to obtain 98-percent combustion efficiency for mixtures of propane and nitrogen.

The conditions which may lead to inefficient combustion in flare flames are graphically shown in Figure 7. The figure was constructed by determining the relative minimum heating value at a given velocity by using the lower 95 percent confidence interval of Figure 4. Figure 7 shows that only one flare flame, operated at a heating value more than 10 percent above the minimum, resulted in combustion efficiencies less than 98 percent. The scatter in the data near the stability limit of the flame is thought to be caused by the difficulty of operating a flame near the stability limit.

Conclusions

1) Techniques developed and used in this study accurately determined the hydrocarbon destruction efficiency of flares over a range of operating conditions.

2) Soot accounts for less than 0.5 percent of the unburned hydrocarbons emitted by flares.

3) The size (diameter) of the flare head did not influence combustion efficiency.

4) Flame stability did influence combustion efficiency. Flares operating with stable flames achieved combustion efficiencies greater than 98 percent. A relationship was developed between gas heating value and exit velocity to describe the region of flame instability.

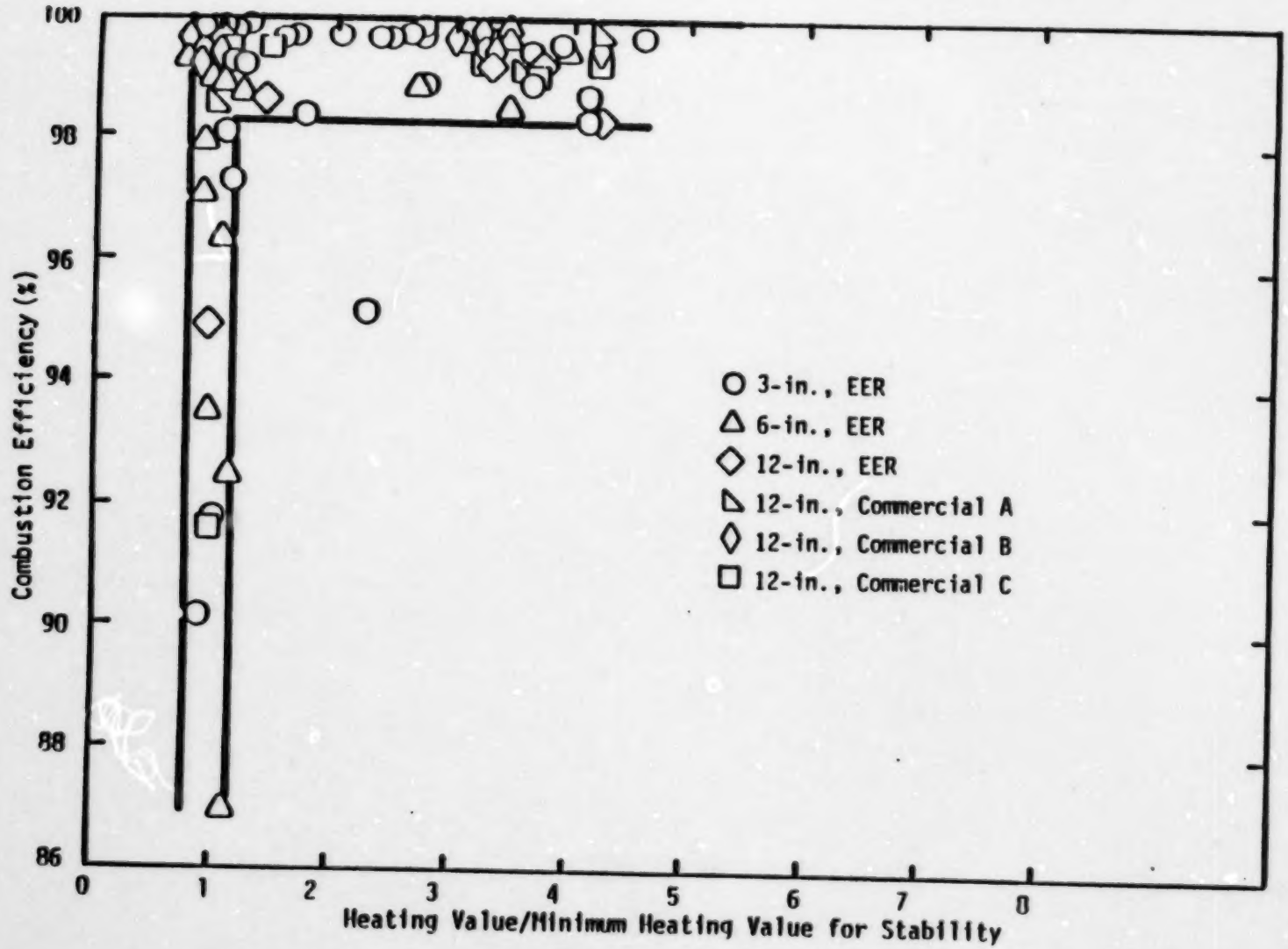


Figure 7. Combustion efficiency near the limits of flame stability.

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Metric Equivalent

To convert nonmetric units used in this paper for the reader's convenience, to their metric equivalents, please use the following conversions.

Nonmetric	Times	Yields Metric
Btu	1.055	kJ
ft	0.305	m
ft^3	28.3	liters
HP	9.809	kW
in.	2.54	cm
$in.^2$	6.45	cm^2
lb	0.454	kg
ton	907	kg